AN ASSESSMENT ON HEAT SOURCE OF GEOTHERMAL FIELDS IN BUYUK MENDERES AND GEDIZ GRABENS, SW TURKEY

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Abstract— The extensional stress regime is very effective in western Turkey since the Oligocene. Geothermal fields are positioned on the high-angle normal faults on the hanging wall of the detachment faults along the northern and southern margins of the Buyuk Menderes and Gediz grabens, respectively. The alignments of the geothermal fields with high temperatures on the both sides of the detachment fault are remarkable. This situation raises the question that whether it is only a channel for the hot waters of the shear zones, or is it a physical mechanism that increases the existing geothermal gradient by creating friction heat. The shallow mantle of a thinned crust (33 km) is the heat source due to large extension rates, resulting in increased heat flow. The high deformation rates of the detachment faults and the fairly high exhumation rate of the central Menderes metamorphic core complex during continental extension could cause an extra heat flow.

Index Terms—Buyuk Menderes graben, detachment fault, extensional tectonics, shear heating.

I. INTRODUCTION

The study area includes the northern and southern margin of the Buyuk Menderes and Gediz grabens in western Turkey, respectively (Fig. 1). Western Turkey has subject to the roughly north-south extension (~30-60 mm/yr), resulting in an approximately E-W directed a graben system [1].

The nature of the heat source for the geothermal systems of western Anatolia is up for debate. Both the Buyuk Menderes and Gediz grabens have typical high enthalpy geothermal fields (Kızıldere, Salavatli, Germencik, Kurşunlu, Göbekli and Kavaklıdere Fig 1).

Although some present models of the geothermal field heat source in the study area suggest a probable magmatic intrusion [e.g. 2], no evidence exists for the presence of a present-day magmatic activity [3]. The heat source for the waters of the Menderes and Gediz grabens has been associated with young tectonic activity resulting from the absence of magmatic activity in the region [e.g. 4].

Reference [5] stated that basins adjacent to detachment faults experienced elevated peak temperatures during stages of the extension. The heat generated by the deformation of the rocks within the shear zone of the detachment, also known as shear heating, played a role in the thermal evolution of the entire region during the extension and could have induced the elevated peak temperatures of the detachment basins.

Although the resulting temperature gradients can clearly be documented geologically in nature and its role during deformation and metamorphism is still controversial [5]- [19].

The first law of thermodynamics, known as the law of conservation of energy, states that energy can neither be created nor destroyed; essentially, it is converted from one form to another. Shear heating is a temperature rise due to viscous dissipation. Strain heating is results of the conversion of mechanical energy into heat during progressive deformation [9, 14]. Reference [9] suggested that temperature rises of a few hundred degrees can be expected in major shear zones. Especially in plastic material production technology, the effects of shear heating are more obvious. The effects of the phenomenon of shear heating are clearly visible in the injection molding process. Namely, during injection molding, the pressure driven flow consists of both internal and kinetic energy where its mechanical energy is transferred into heat energy. The combination of the relatively high viscosity and high shear rates can result in significant viscous dissipation. The high energy is required to pressurize driving the melt through a closed channel. It is a result of the high frictional forces developed between the constant walls of the channel and the flowing the melt. As flow is laminar during injection molding, the highest shear rates are in the outer layers adjacent to the constant wall and in the center of the channel it drops down to zero. Consequently, the shear heating is concentrated in the outer layers where shear rates are highest (Fig 2, [20]).

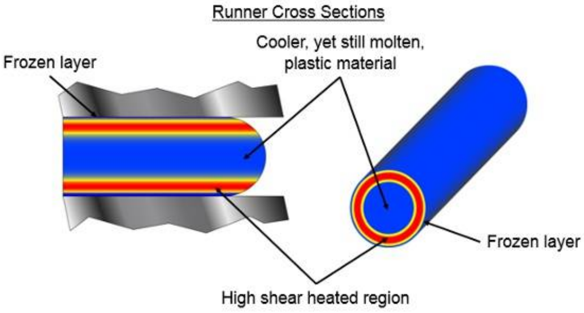

Fig 2. Temperature difference in runner cross sections.

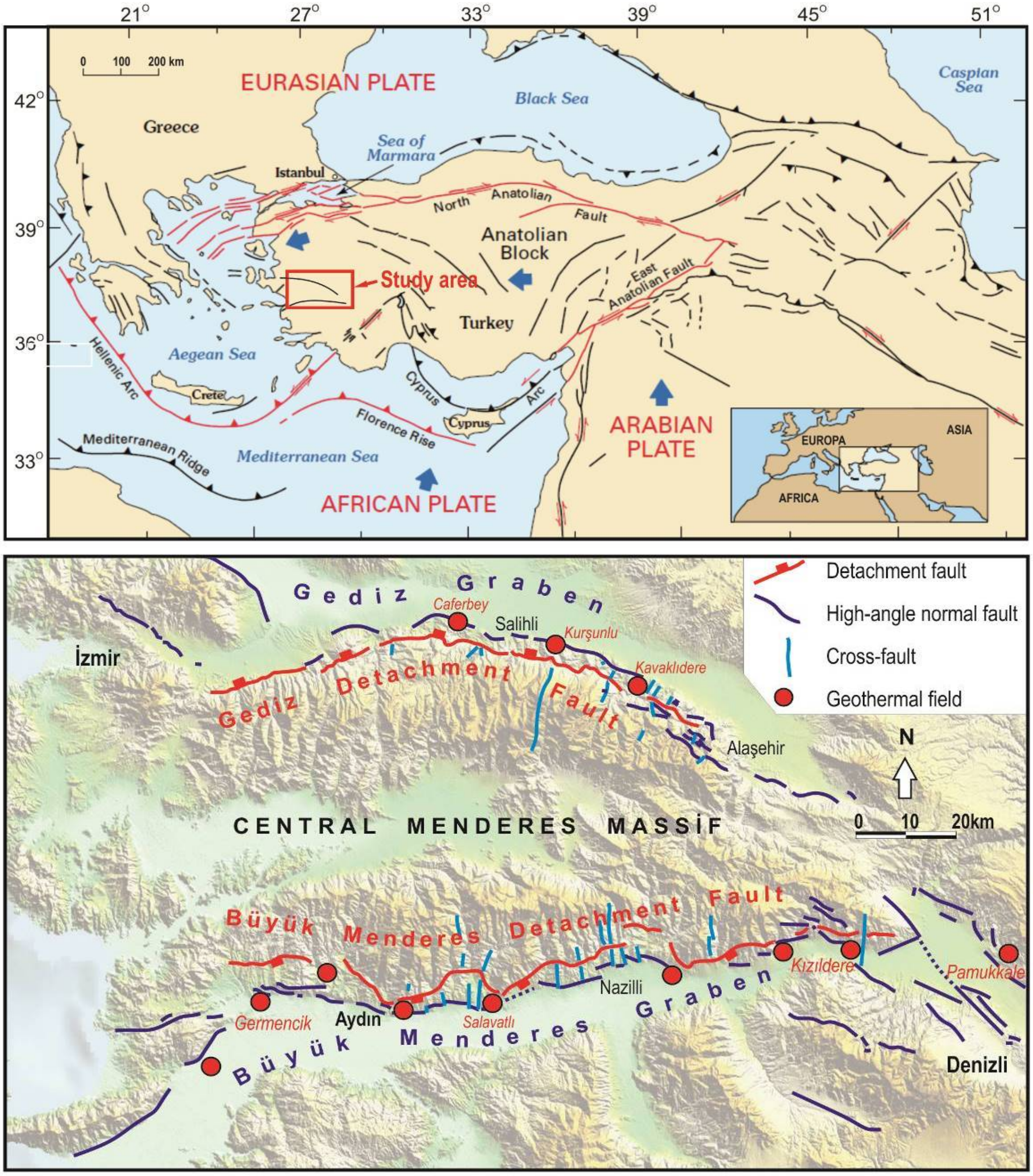

Fig. 1 Tectonic map of Turkey (modified from USGS, above), location map of the study area and structural positions of the geothermal areas developed in front of Buyuk Menderes and Gediz detachment faults (below) [3].

The result is that significantly non-homogeneous melt temperature distributions are developed in the melt during molding. This situation causes significant structural defects during molding of the melt material [20].

II. GEOLOGICAL SETTING

A major south-dipping normal fault system bounds the northern margin of the E-W striking Buyuk Menderes graben (Fig. 1). The normal faults juxtapose Neogene sedimentary units against the metamorphics of the Menderes massif.

Metamorphic rocks exposed the study area is located between the Buyuk Menderes and Gediz grabens, consisting of Menderes massif (Central Menderes Massif), in the Odemis-Kiraz region. The Menderes massif regionally exposed as basement rock consists of quartz-muscovite schist, biotite-quartz schist, garnet micaschist and augen gneiss. The Neogene (Miocene-Pliocene) sequent consists of fluvial and lacustrine sediments in the study area are covered by Quaternary colluvium and alluvium. Western Turkey has undergone significant approximately N-S extension, reaching 20 mm/yr [21], this value is correspond to a deformation rate approximately 65 nano-strain/yr. The timing of the initiation of this extension is a controversial and varies among studies from Early Oligocene to Pliocene-Pleistocene [22, 23, 24, 25, 26, 28].

The Central Menderes Massif core-complex which has exhumated on the footwalls of south facing of Buyuk Menderes detachment and north facing of Gediz detachment in the south and in the north respectively [29, 30, 31].

The exhumation of the Central Menderes Massif core complex which is bounded by the Buyuk Menderes and Gediz detachment faults from southern and northern sides respectively, is bivergent continental breakaway zone in the western Turkey [30]. It has started in the Latest Oligocene-Early Miocene [23, 29, 30]. According to reference [32], the Menderes massif was exposed the Early Miocene tectonic denudation and surface uplift in the footwall of a north-south directed extensional detachment system, followed by the Late Miocene to recent fragmentation by E-W and NW-SE trending graben systems.

Buyuk Menderes detachment fault is commonly S-dipping with a small right-lateral strike-slip component. Dip values vary from 40° to 65°. It is running along the northern margin of the Buyuk Menderes graben, and is approximately E-W directed (Fig. 3). Along the southern margin of the Alaşehir graben, Gediz detachment fault is generally N-dipping with dips ranging between 15°-20° [3].

Reference [2] determined the geothermal gradient values in the Kızıldere geothermal field were determined as 1 to 10 °C/ 10 m for depths varying between 80-250 m in the region.

III. DISCUSSIONS ON ORIGIN OF HEAT SOURCE

The Aegean region contains common Neogene volcanic rocks. Volcanic activity has been widespread in western Turkey since the Late Eocene and is associated with the Eocene continent-arc collision, which continued into Holocene [33]. Early Miocene aged actual granodioritic rocks (Salihli and Turgutlu granodiorite) have been found 50 km north of the study area (Bozdağ region) and to the north of the Ödemiş-Kiraz submassif [29]. Furthermore, the Quaternary Kula volcanics, located approximately 60 km north of the study area. In this context, the youngest volcanic activity in the region, represented by Kula volcanics, should not to be a heat source origin because of the long distance and lack of recent magmatic activity [3]. Similarly, reference [4] noted that the lack of significant actual magmatic activity indicates that the upper levels of the crust are not a direct heat source for geothermal activity in western Turkey. These authors suggest that most of the geothermal activity in the region is of amagmatic origin [3]. Therefore, the heat source seems to be associated with crustal detachment faulting, in tectonic settings where magmatic activity is absent.

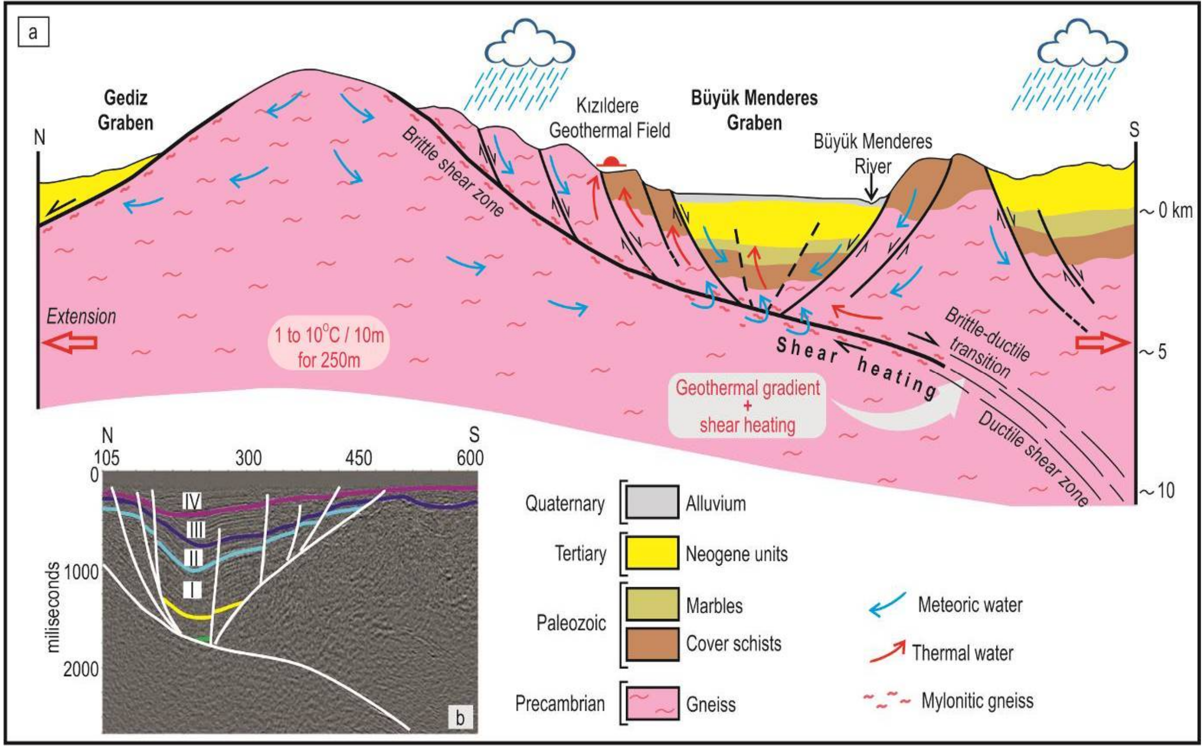

Fig. 3 a) A conceptual model of geothermal circulation in the study area, (b) a deep seismic profile with the N-S direction taken from a 30 km west of study area, Nazilli region [34]. Roman numerals indicate the different sedimentary sequences [3].

The Aegean region is one of the world's most active tectonic areas. The fault slip rates obtained from GPS-derived velocity field data from the study area reveal that the total motion of approximately 25 mm/yr corresponds to 10.9 ± 0.3 mm/yr of the left-lateral strike-slip and 14.5 ± 0.3 mm/yr of the normal slip or extension [21]. These slip rate values correspond to deformation ratios (ε) from $0.45x10^{-9}$ s^{-1} (for normal slip) to $8x10^{-8}$ s^{-1} (for total motion) [3].

Buyuk Menderes and Gediz detachment faults (shear zones) that limited from the northern and southern margins of the CMM, which were developed due to thinned-crust tectonics within the ductile-brittle transition zone at the upper levels of the continental crust (Fig. 3a).

The presence of low-angle S-dipping detachment faults in the Buyuk Menderes graben was confirmed using conventional deep seismic reflection and gravity data defined, Moho depth is located at ~33 km (Fig. 3b, [34]).

The focal depths of earthquakes in the Buyuk Menderes graben were distributed at depths of 5 to 13 km and were concentrated at depths of 5 to 6 km [3]. These data may be correspond to lithostatic pressure of ~ 130 MPa and to shear stress of ~ 110 MPa on the basis of depth (5 km) and dipping (25°) of a major detachment fault plane [3]. The calculated shear stress and deformation rate values are consistent with the values of reference [10], which may indicate the required high strain-rates and shear stresses (10^{-11} – 10^{-12} s^{-1} and ~100 MPa) for heat production in a shear zone, for a possible heat increase added to the existing high heat flow [3].

Thermochronological data indicates two-phase exhumation history of the footwall of the Buyuk Menderes detachment fault since the middle Miocene. The first phase of accelerated exhumation occurred in the Middle Miocene at a rate of ~0.9 km/Ma. The second phase of exhumation proceeded in the Pliocene, when the Buyuk Menderes detachment operated at a slip rate of 3.0 (+1.1/-0.6) km/Ma [3].

Principally, strain-related heating resulted from the conversion of mechanical energy into heat during progressive deformation in narrow zones [9]. Therefore, heating is an important crustal phenomenon that could be integrated into large-scale tectonic models. Although the resulting temperature gradients can be determined geologically, the evidence is unambiguously documented in nature and its role during deformation and metamorphism remains controversial [9, 14].

Reference [5] stated that heat generated by the deformation of the rocks within the shear zone of the detachment (also known as shear heating). They numerically analysed the influence of the rheology and the deformation style within the shear zone, the rate of exhumation of the footwall, and the thickness of the sedimentary accumulation on the top of the system. The model reproduces the elevated temperatures recorded in the supra-detachment basins where locally 100 °C and 25% of the total heat budget can be attributed to shear heating.

Several proposals for the heating of geothermal fluids through tectonic activity are summarised below:

Heat is generated by the friction between two blocks during earthquakes [36] and is also slowly produced in association with friction events along the brittle-ductile shear zones in the upper levels of the continental crust [e.g., 7, 11, 17, 18]. The amount of shear heating is mainly dependent on the exhumation rate and the rheological parameters of the rocks [5].The localised temperatures of the shear zones at shallow crustal levels are ~200 °C, which are higher than those of surrounding rocks in the Musgrove Block, central Australia [11]. Heating on the fault plane is maximum grade at a small distance above the base of the fault [12]. In deeper parts of the strike-slip faults, shear heating would predictably cause strain localization [8]. Heat flow can develop during extensional tectonics if the strain rate of that activity at the upper continental crust is rapid [13]. Similar results have also been obtained in other studies; in the detachment zones, accumulated strain may have a significant effect on the heat budget of the system [7, 9, 16, 37]. Likewise, mineral transformations in the fault damage zones, such as the increasing percentage of illite in mixed-layered illite-smectite [17], exhibit temperature increases of up to 150 °C towards the fault core.

Reference [6] calculated that, if depth-averaged shear stress on the fault was in excess of 50 MPa, the temperature increase induced by shear heating could lead to argon degassing.

Reference [8] are systematically explored that variations of several independent parameters and their influence on the thermo-mechanical state of the fault zone and on shear heating. Accordingly, shear heating is found to be more important in fault zones affecting an initially cold lithosphere, and increases with slip rate, friction coefficient and stiffness of materials. They stated that in extreme cases (slip rate of 10 cm yr^{-1}, stiff lithosphere), shear heating could lead to temperature increases close to 590 °C at the Moho, and 475 °C at 20 km depth.

A similar assessment was made by reference [19]. He expresses that in plate-boundary scale ductile shear zones defined by microstructural weakening, shear heating may lead to a temperature increase over 5 my of up to 80 °C just below the brittle ductile transition, up to 120 °C just below the Moho [19].

Reference [15] demonstrated that the strain distribution of the two models shows that the colder lithosphere has localized shear zones (Fig. 4a), whereas the hotter lithosphere is characterized by diffuse deformation (Fig 4b). The colder model is characterized by high strain shear bands surrounding weakly strained blocks. In contrast, the hotter case has lower strain shear bands and widespread straining of intervening blocks.

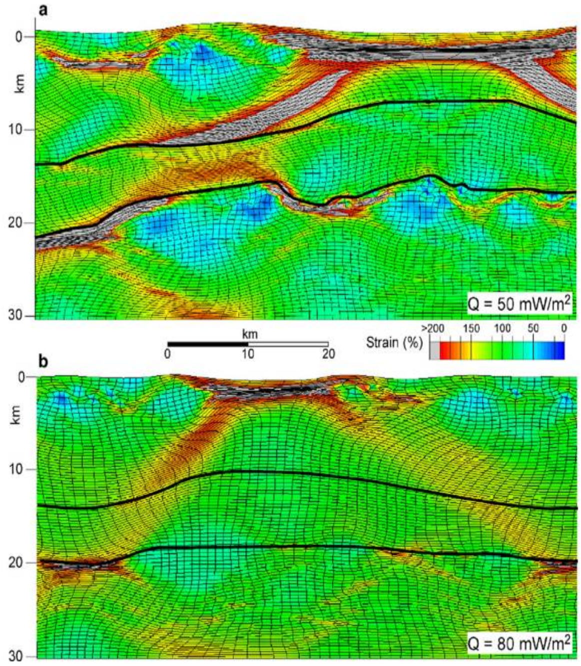

Fig. 4 Finite strain distribution after 13.7 Ma and β = 2.6 for models with initial crustal thickness of 50 km and heat flow of (a) 50 mW/m^2, (b) 80 mW/m^2. The two thin black lines define boundaries between quartz-, feldspar- and olivine-dominated layers, with the lower line corresponding to the base of the crust (Moho). β: the strain accumulated during a single stress loading/deformation event [15].

That is, according to the model of reference [15] localized high strain shear zones that are relatively stiff, relatively high in shear rate and coefficient of friction than hot lithosphere may be considered to be more likely to occur shear heating phenomenon.

In order to form the shear heating, minimum shear stress [7, 10]; minimum deformation rate [10] and minimum slip rate should be 50-100 MPa, $10^{-11} – 10^{-12}$ s^{-1}, 10 cm yr^{-1} [8] respectively. Additionally exhumation rate of the footwall the detachment fault should be also high. The values in the study area are 110 MPa, $0.45x10^{-9}$ s^{-1} (for normal slip) and $8x10^{-8}$ s-1 (for total motion) and 14.5 ± 0.3 mm/yr (for normal slip) are shear stress, deformation rate and slip rate respectively. Moreover, the exhumation rate reaches up to 3 km/Ma [35]. In other words, all the geo-kinematic conditions are suitable for the shear heating.

The high heat flow values (140 mVm^{-2}) have been observed at the margins of the northern Buyuk Menderes and the southern Gediz grabens (Fig. 5, [38]). The high heat flow corresponds to the places where tectonically active current [3]. The highest heat flow values in the region are remarkably perfect harmony with detachment faults (Fig.1 and 5). This indicates that the detachment faults are not only a channel in the circulation of hot water, but may also be a heat source.

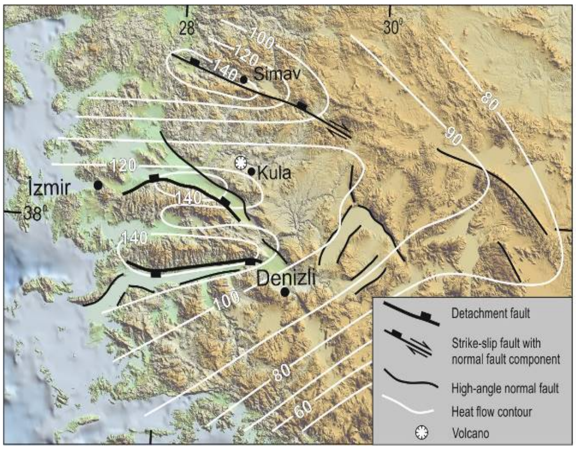

Fig. 5 Heat-flow distribution map (modified from [38] combined with active tectonic lines of the western Turkey (contour value, mVm^{-2}) [3].

Heat sources for thermal fields with high reservoir temperatures (142 °C to 242 °C from deep-geothermal wells on the northern side of the Menderes graben (Fig. 1) does not seem to originate from magmatic activity [3]. This is because there is no trace of recent magmatism along the 165 km range, but tectonism is active and intense throughout the graben. These high-dipping faults are connected to a low-angle (θ=20 - 25°) major detachment fault at shallow depths (6-13 km, Figs. 3a and b, [34]). It is estimated that this detachment fault at a depth of about 5 km has a low-angle, such as about 20 ° to 25 °, The relatively low-angle at this level of the fault causes higher shear stress and deformation rates where friction/shear generates possible heat sources for thermal fields along the Buyuk Menderes graben.

The highest reservoir temperatures of the thermal fields along the Buyuk Menderes (such as Kızıldere 242 °C and Germencik 232 °C) and Gediz detachment faults (such as Salihli-Kurşunlu 168 °C, Salihli-Göbekli 182 °C and Alaşehir-Kavaklıdere 213 °C) are observed in the field (Fig. 1). Geothermal resources aligned on both of the northern and southern edges of detachment faults demonstrate that the heating source is related to active tectonism (shear heating) rather than a magmatic origin.

CONCLUSION

The E-W oriented Buyuk Menderes and Gediz grabens contains a number of geothermal fields along its northern and southern margin, respectively.

The highest heat flow values in the region remarkably perfect harmony with detachment faults. This indicates that the detachment faults are not facilitate a channel in the circulation of fluids flow, but also a possible heat source.

The elevated mantle due to N-S crustal extension and thinned controlled by current tectonic activity in western Turkey, heat source of the geothermal fields in the Buyuk Menderes and Gediz grabens.

Shear heating phenomenon in the localized shear zones in the upper levels of the crust is more effective in the harder and colder sections of the crust than in the lower ductile levels due to the deformation rate and the higher coefficient of friction.

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